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INFLUENCE OF ANTHROPOGENIC MEASURES ON SEDIMENT TRANSPORT CHARACTERISTICS IN THE ELBE ESTUARY - HINDCAST STUDIES ON DIFFERENT HISTORICAL STATES WITH A THREE-DIMENSIONAL MODEL

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ABSTRACT

The River Elbe has its source in Czechia, flows through Germany and meets the North Sea. The estuarine part represents the most important waterway for Germany. Already centuries ago the river was deepened several times, narrow curves had been alleviated, section of large widths had been narrowed by structural measures and so the Elbe estuary was continuously adapted to the changing conditions of the maritime traffic. Nevertheless it is still necessary to maintain the channel by dredging and to build structural measures to guarantee the safety of the shipping traffic, the bank, dikes and last but not least the people.

All these anthropogenic measures caused changes in the hydrodynamic and the sediment transport behavior of the Elbe estuary. A scientific investigation and system analysis e.g. on construction measures in this estuary is necessary to achieve a better understanding of this system. This knowledge is needed to find solutions for a reduction of maintenance dredging or other recent economical and ecological problems. One important method is the use of numerical models for studies of the sediment transport regime and the morphodynamical behavior.

Different bathymetries representing the state of the years 1970, 1997 and 2002 are computed with a three-dimensional model of the Elbe estuary. In this period the fairway was deepened twice and several structures had been built. The sediment transport characteristics of these model runs will be analyzed and compared to each other. In that way the influence of man made measures like deepening of the fairway can be estimated. This knowledge can be used to evaluate measures which are planned for the future.

1. INTRODUCTION

The mouth of the Elbe estuary is situated in the south-east of the German Bight (Figure 1), the weir Geesthacht is the tidal barrier. The length from the weir to the mouth is more than 160 km. The mouth has a width of approximately 15 km. Its bathymetry is characterized by a deep fairway to the harbor of Hamburg and a complex system of channels and large tidal flats in the outer estuary.

The Elbe is a strong anthropogenic influenced estuary. Several deepening had taken place in the last 140 years. Between 1860 and 1999 the fairway was deepened up to 10 m, schematic shown in Figure 2. Consequently the tidal characteristics changed. Figure 3 shows the mean high water and the mean low water at a tidal gage in St. Pauli, Hamburg, from 1870 to 2005. The tidal range increased considerable (1 m in the last 35 years) due to a decrease of the low water level and an increase of the high water level.

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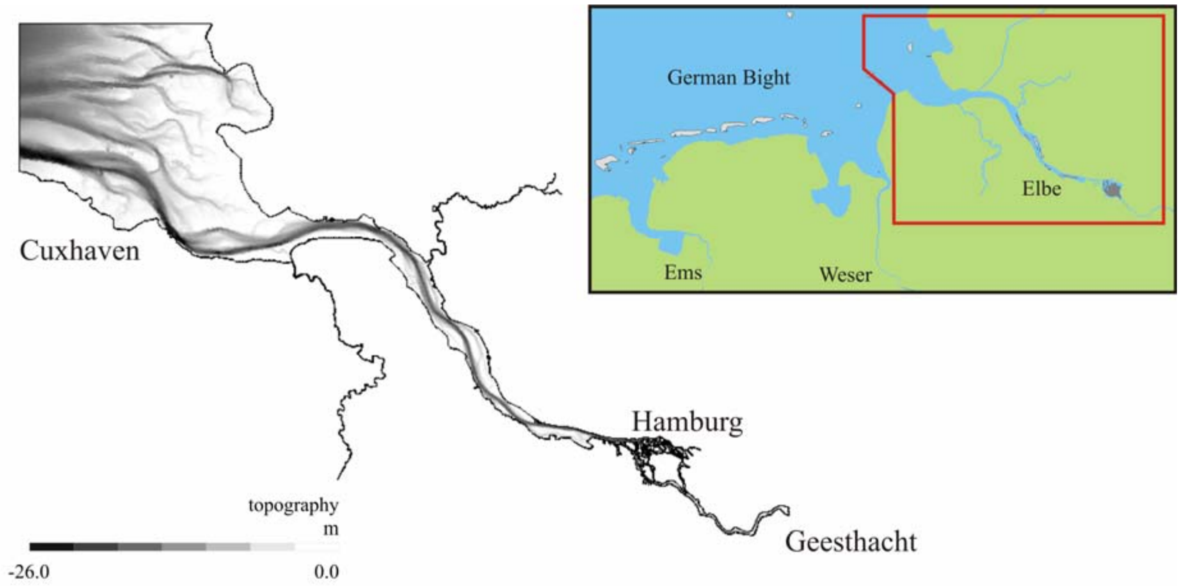

Figure 1 Geographical positions and denotations of the Elbe estuary.

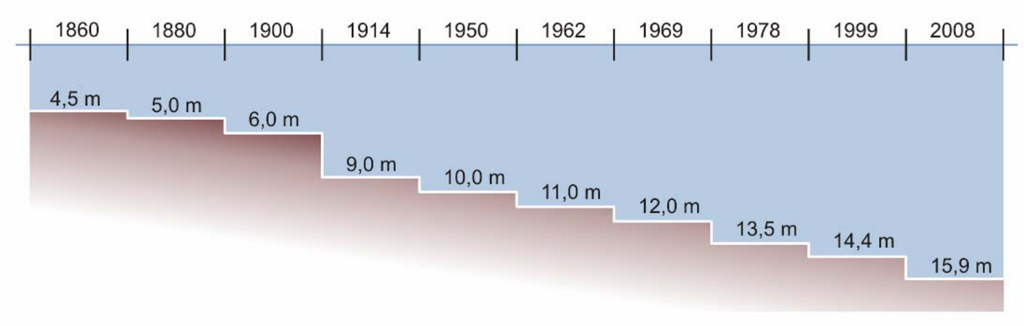

Figure 2 Depth of the fairway of the Elbe estuary from 1860 to 2008 [German newspaper: Hamburger Abendblatt, 22.08.2006, modified].

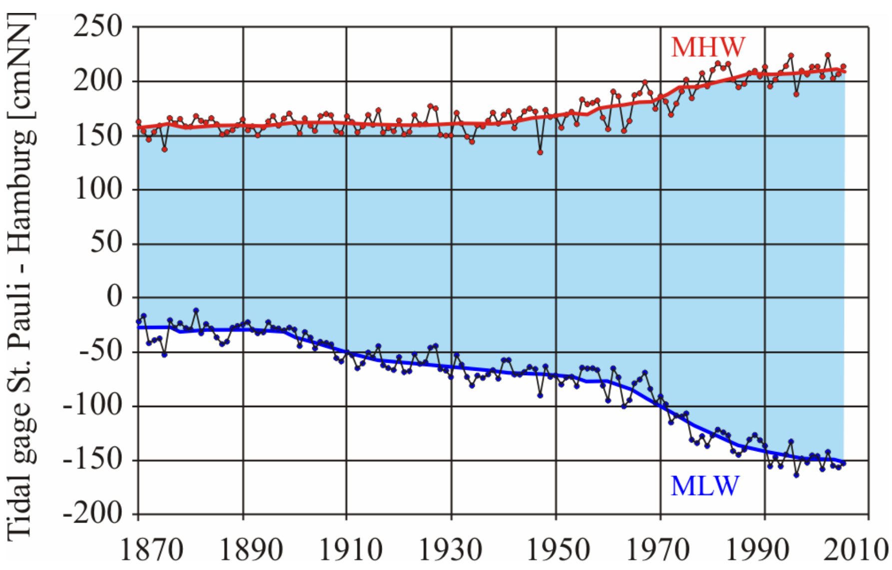

Figure 3 Mean high water and mean low water from 1870 to 2005 at a tidal gage in St. Pauli, Hamburg [Duecker et al., HANSA - International Maritime Journal, 2006, modified].

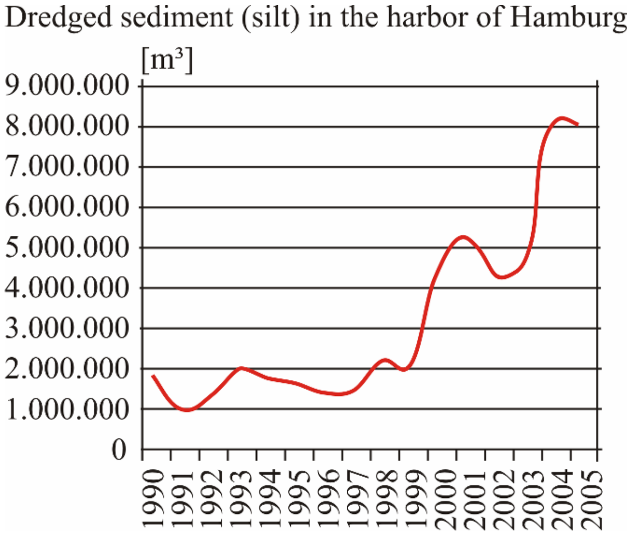

Figure 4 Amount of maintenance dredging in the harbor of Hamburg from 1990 to 2004 [Duecker et al., HANSA - International Maritime Journal, 2006, modified].

In the last 30 years the fairway was deepened twice and several structures had been built. In 1969 the deepening of the fairway to 12.0 m was completed. Already five years later between 1974 and 1978 it was deepened to 13.5 m and broadened at many locations. Between 1970 and 1985 a lot of material was removed from the Elbe estuary for the construction of dikes for flood protection. Since 1999 the maintained depth of the fairway is 14.4 m.

After the last deepening in 1999 the amount of maintenance dredging especially in the harbor of Hamburg increased significantly (Figure 4). This is an important reason for a scientific investigation and system analysis on hydrodynamic effects of several anthropogenic measures in this estuary. The aim of this study is to get knowledge of the sediment transport regime and the reason for its changes in the last decades. The behavior of this estuary must be understood in order to achieve a reduction of maintenance dredging and to improve the hydrological and ecological system all in all. One helpful important method for this task is the use of numerical models.

2. NUMERICAL MODELS

For computation of the transport processes in the Elbe estuary, the hydrodynamic / sediment transport model UNTRIM (Casulli & Walters (2000), Casulli & Zanolli (2002)) was coupled with the morphological model SEDIMORPH, both well validated and continuously developed models. UNTRIM is a computational model to solve various two- and three-dimensional differential equations related to hydrostatic and non-hydrostatic free-surface problems[3] and suspended sediment transport. SEDIMORPH is a software package for two- or three-dimensional simulation of fractioned sediment transport processes within the bottom and at the bottom surface which can be combined with different hydrodynamic models[4]. The most important features of the simulation software are subsequent briefly described.

[3] http://www.baw.de/vip/abteilungen/wbk/Methoden/hnm/untrim/PDF/vd-untrim.pdf
[4] http://www.baw.de/vip/abteilungen/wbk/Methoden/hnm/sedimorph/vd-sedimorph.pdf

2.1 UNTRIM

The hydrodynamical model UNTRIM is based on the continuity equation for incompressible fluids and on the Reynolds-averaged Navier-Stokes-Equations for momentum transport. Furthermore a transport equation for several kinds of active or passive tracers can be solved (Casulli & Zanolli (2004)). The algorithms implemented in the UNTRIM code work on unstructured orthogonal grids to cover problems with complicated geometries. Based on a two-dimensional horizontal mesh, a three-dimensional topology can be constructed after definition of vertical z-layers (Casulli & Zanolli (2004)).

Density effects are represented by an equation of state related to temperature and salinity and additional sediment mass concentrations. In case of vertical density gradients damping or enhancing of the vertical viscosity, which is calculated with a mixing length model, can be modeled using Munk-Anderson damping functions (Lang, G. (2005)).

At BAW-Hamburg UNTRIM is coupled directly with the morphological module SEDIMORPH. In the present stage of this implementation suspended matter can either be modeled as cohesive or non-cohesive sediment. If suspended matter has non-cohesive properties any number of suspended sediment fractions can be defined in order to represent the sediment transport in the water column. A flocculation model for fractioned suspended sediments is not yet implemented. In this case each suspended sediment fraction has an individual constant settling velocity which depends on sediment properties (grain size, density, shape) and is calculated using settling velocity formulas from Stokes or Dietrich. If suspended sediments have cohesive properties, only one suspended sediment fraction is taken into account. In this case the local settling velocity is e.g. a function of the local sediment concentration and the local turbulence and cohesive sediment properties like flocculation or break up are considered in such a parameterized way (Weilbeer, H. (2005)).

2.2 SEDIMORPH

The development of the morphological module SEDIMORPH was initiated by BAW-Hamburg. Meanwhile, this software is used and developed in a framework of several hydraulic research institutes. The primary purpose of SEDIMORPH is to compute the sedimentological processes at the alluvial bed of a free surface flow. These processes include

- the roughness of the bed resulting from grain and form roughness (ripples and / or dunes)
- the bottom shear stress as a result of roughness and flow
- the bed load transport rates (fractioned)
- erosion rates (fractioned)
- the bed evolution itself
- sediment distribution
- porosity prediction

SEDIMORPH is designed as a multi component model in which sediment names, types and properties (grain size, density et al.) are defined by the user. In this way SEDIMORPH can use any system of sediment classification. This can be the Udden-Wentworth scale which was used for this study, but also any other classification (Malcherek et al. (2005)).

SEDIMORPH uses the same computational mesh as the hydrodynamical model, i.e. it can work on structured as well as on unstructured grids. It is designed to treat two- or three-dimensional simulation of fractioned sediment transport processes within the bottom and at the bottom surface layer. Figure 5 shows the structure of the morphological dataset. The construction of a three-dimensional mesh follows exactly the same procedure as for the hydrodynamical model. For short- or medium-term applications, a three-dimensional dataset is not required. In present applications of SEDIMORPH, two-dimensional datasets are used i.e. a detailed distribution of bottom surface sediments for the model domain must be prescribed. Furthermore a variable non-erodable horizon (or rigid layer) is included. Another necessary feature of morphological modules is the consideration of at least one exchange layer in which sediments are mixed and exchange processes with the water body are modeled. The exchange layer is defined as the upper part of the bottom surface layer.

During a model run the hydrodynamic model passes either the total water depth and the depth averaged velocity (2D) or the water height of the first cell over the bed and the related velocity (3D) to SEDIMORPH. Using this hydrodynamic information, SEDIMORPH calculates the bottom shear stress (Nikuradse law) due to the grain roughness influenced from the local sediment distribution. If a wave model is considered the bed shear stress will be modified (Knoch & Malcherek (2005)). Bed load transport capacities and rates are computed completely inside SEDIMORPH. In case of suspended sediment transport SEDIMORPH gets deposition fluxes from the hydrodynamic model and sets itself erosion fluxes. Finally the bottom evolution is calculated and the sediment distribution in the exchange layer and in the lower cells is updated.

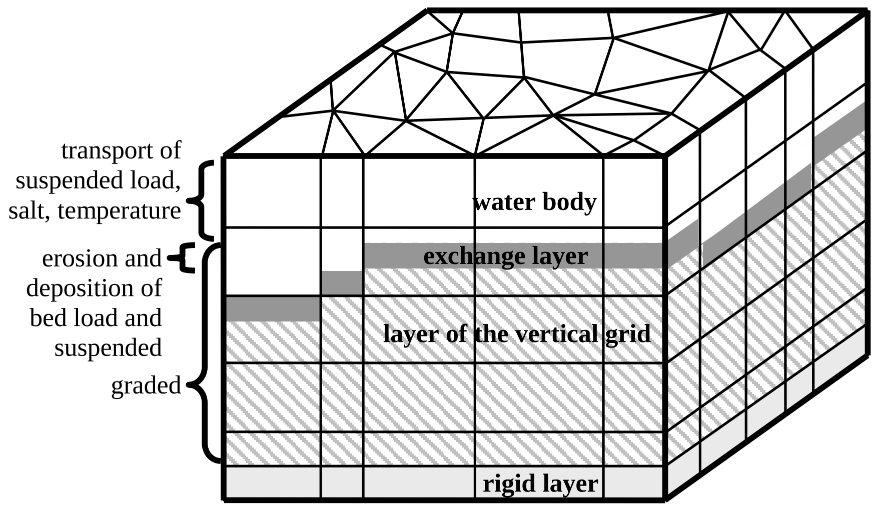

Figure 5 Structure of the morphological data set in SEDIMORPH.

2.3 Initial physical dataset, model control and modeling strategy

The model domain covers the area shown in Figure 1 (left hand side). The computational mesh is constructed using triangular and quadrangular elements and consists of nearly 140,000 two-dimensional polygons. The three-dimensional topology uses vertical layers of 1 m thickness, so the computational mesh comprises more than 1,000,000 elements. The length of the edges varies between 1.46 m and nearly 1,400 m. Most of the elements have a length of about 50 m.

An initial physical dataset was defined in order to initialize the model not only with hydrodynamic conditions, but also with elaborated morphological descriptions. Depending on the chosen sediment types to be used for a study a local varying distribution of sediment fractions must be prescribed for each polygon of the model domain. This information could stem e.g. from sediment probes or geological maps. Due to definitions of regions with fixed features and / or due to inter- or extrapolation of measured data a coherent and consistent morphological dataset has to be created. Morphological data for the model of the Elbe estuary are based on more than 1,000 recent sediment samples. The sediment distribution is described with seven sediment fractions classified following the Udden-Wentworth scale. Five sandy sediment fractions (very fine sand, fine sand, medium sand, coarse sand, very coarse sand) are defined to represent bed load transport, and two suspended sediment fractions (medium silt, coarse silt) were chosen for modeling fractioned suspended sediment transport.

In Figure 6 the mean particle diameter of the resulting initial sediment distribution is shown. The shallow water areas are dominated by fine sediments with mean particle diameters between 0.10 mm and 0.20 mm. In deeper parts of the estuary coarser sediments with mean particle diameters of more than 0.50 mm are found. The bottom roughness used in the model is calculated as a function of the grain roughness, i.e. it is initialized with the definition of the morphological dataset, and variable during a model run. Additionally form roughness parameters were defined in areas with distinct dune dynamics. This was needed for calibration purposes in this model.

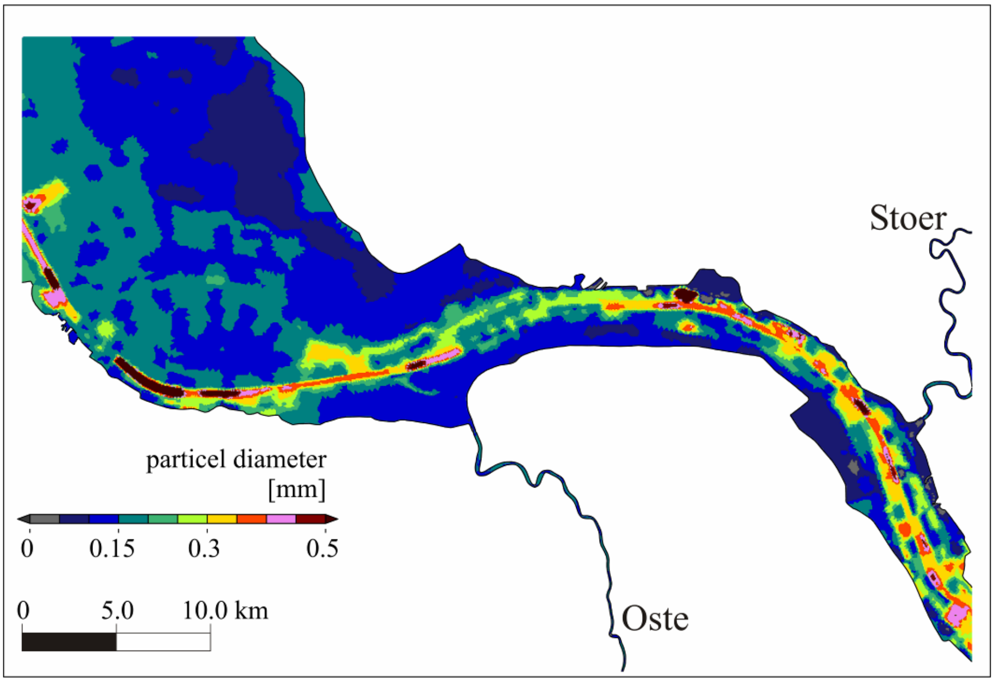

Figure 6 Mean particle diameter distribution in the morphological data set for the Elbe estuary based on sediment samples.

The model is controlled due to prescribed water level elevations at the open boundary at the German Bight (Figure 1) and due to fresh water inflow at the weir Geesthacht and two major tributaries (Stoer and Oste). In the simulated period the fresh water inflow at the weir Geesthacht is given to 350 m^3/s. This is the most frequently value analyzed for ten years (1995 - 2004). The inflow at the tributary Oste is given to 5.0 m^3/s, at the tributary Stoer it is 8.0 m^3/s.

Furthermore the transport of salt is taken into account. The initial salinity concentration is initialized by a graded spatial distribution, estimated from measurements. Its initial vertical distribution is assumed to be constant over the depth.

The model used in this study is calibrated and validated for a bathymetry and a hydrological situation from 2002. The model runs were carried out for the period from May 3rd to May 27th 2002. The water level at the gage Cuxhaven (Outer Elbe estuary) for this time is shown in Figure 7.

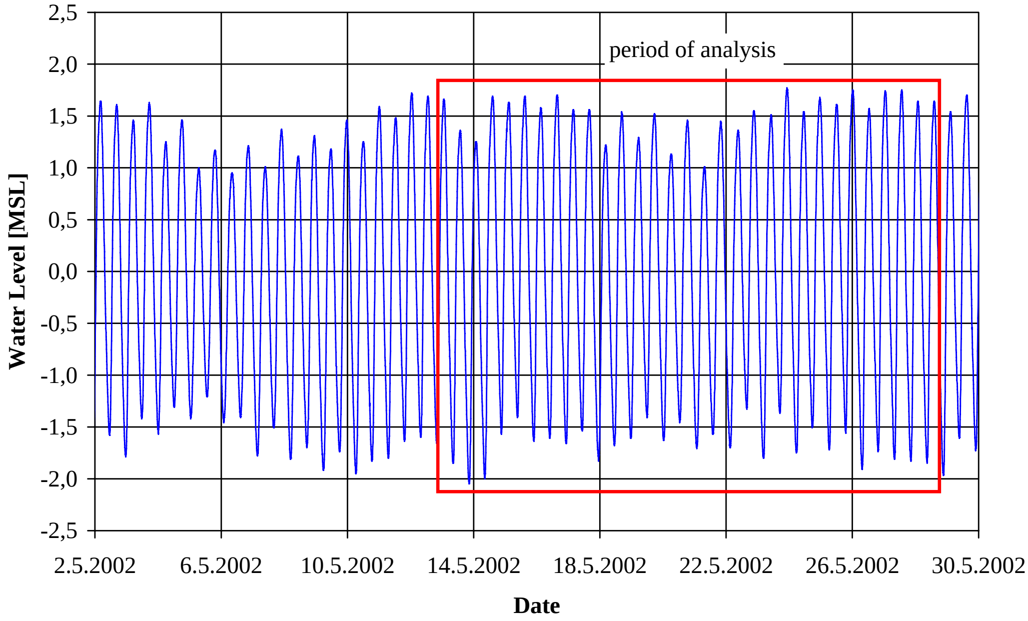

Figure 7 Water level at the gage Cuxhaven (Outer Elbe estuary) during the period of simulation (May 3rd to May 27th 2002) and marking of the period of analysis (May 11th 2002 to May 25th 2002).

In Figure 7 the period of analysis is marked. After a simulation time of eight days the period of analysis is reached. Significant parameters were analyzed for one spring-neap-cycle (May 11th 2002 to May 25th 2002). During this period (27 tides) all model results are stored every ten minutes. In several post-processing steps these data are analyzed not only regarding the minimal, mean and maximal values of water level, velocities, salinity and sediment concentrations for each element, but also regarding the resulting transport across defined cross sections and many other calculable analysis results, which are useful to describe the system behavior in a compact manner. The locations of several cross sections, which are used in the following analysis, are shown in Figure 8. For orientation fixed points in the fairway with an interval of 1 km are defined. The denotations of the cross sections are referred to those points. Thus the suspended sediment flux can be analyzed in a very detailed way. Bed-load transport is also calculated in the model, but not yet considered in this analysis.

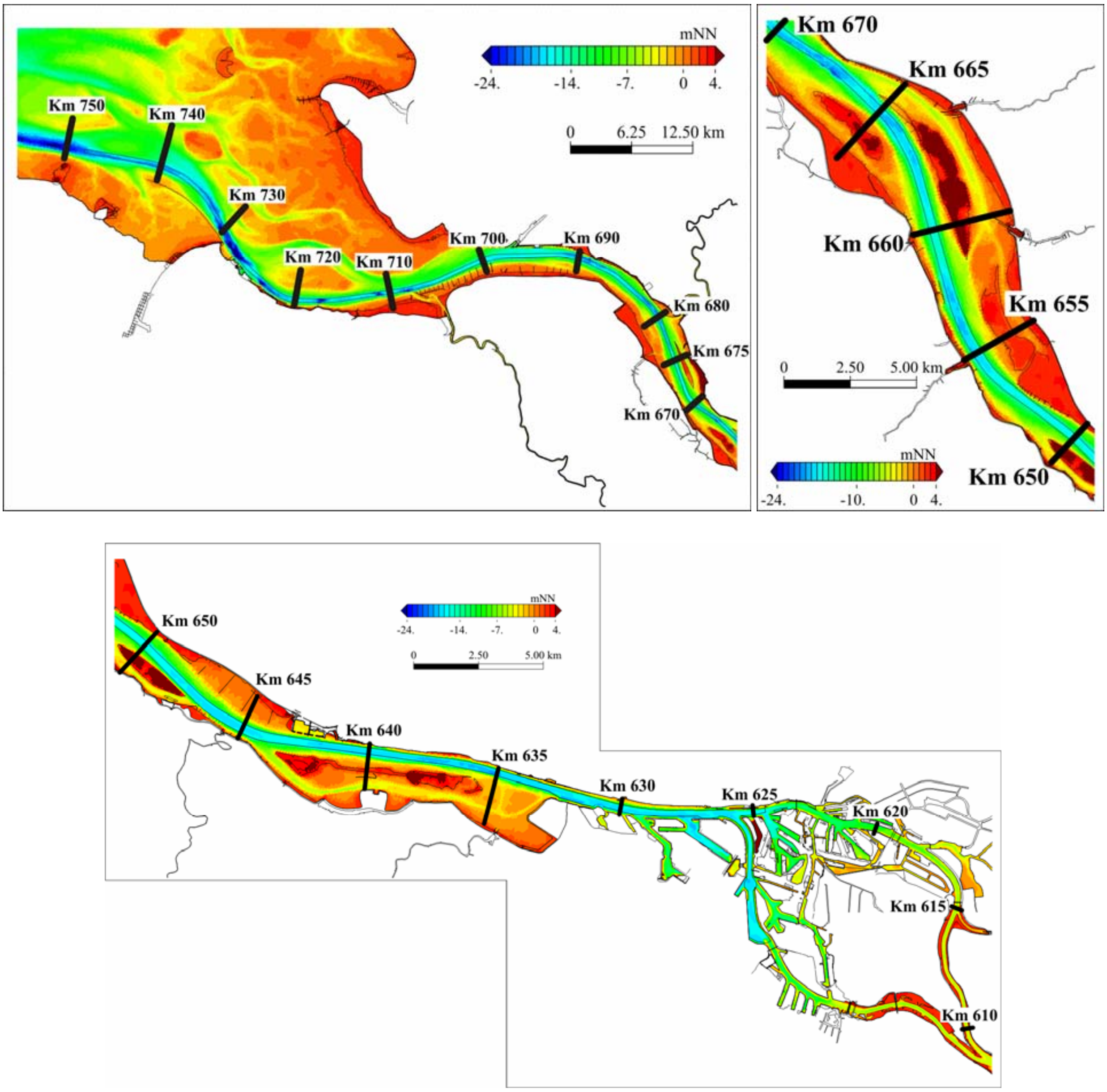

Figure 8 Model domain with denotation of cross sections.

Solely the bathymetry representing the states of the years 1970, 1997 and 2002 was varied to figure out the influence of these changes on hydrodynamic and sediment transport processes. All model steering parameters, initial conditions like sediment and salinity distribution, and all boundary conditions and values were retained.

2.4 Significant morphological changes

The measured depths in a long-section along the middle of the fairway for the different years are shown in Figure 9. As mentioned before the fairway was deepened between 1970 and 1997 as well as between 1997 and 2002. The difference of the depths in the fairway between 1970 and 1997 is larger as the difference of the depths between 1997 and 2002.

In Figure 10 the difference between the bathymetries in a section of the landward part of the estuary is pictured. The blue color indicates erosion, and red color indicates sedimentation. Predominant reasons for these changes are local anthropogenic measures. Erosion dominates these figures, but this “erosion” is mainly caused by the deepening of the fairway. Intensive red colored areas occur because of the landfill of islands with dredged sediments, but weaker red colored areas indicates sedimentation and siltation respectively, caused by hydrodynamic conditions.

The difference of the measured depths in the Outer Elbe between the bathymetries of 1997 and 1970 and between 2002 and 1997 is shown Figure 11. The outer estuary is mainly affected by natural morphodynamics. The most important morphodynamical process is the development of the Medem channel. The tidal channel moves northward up to 100 m per year. Man made influences in the Outer Elbe are rather small.

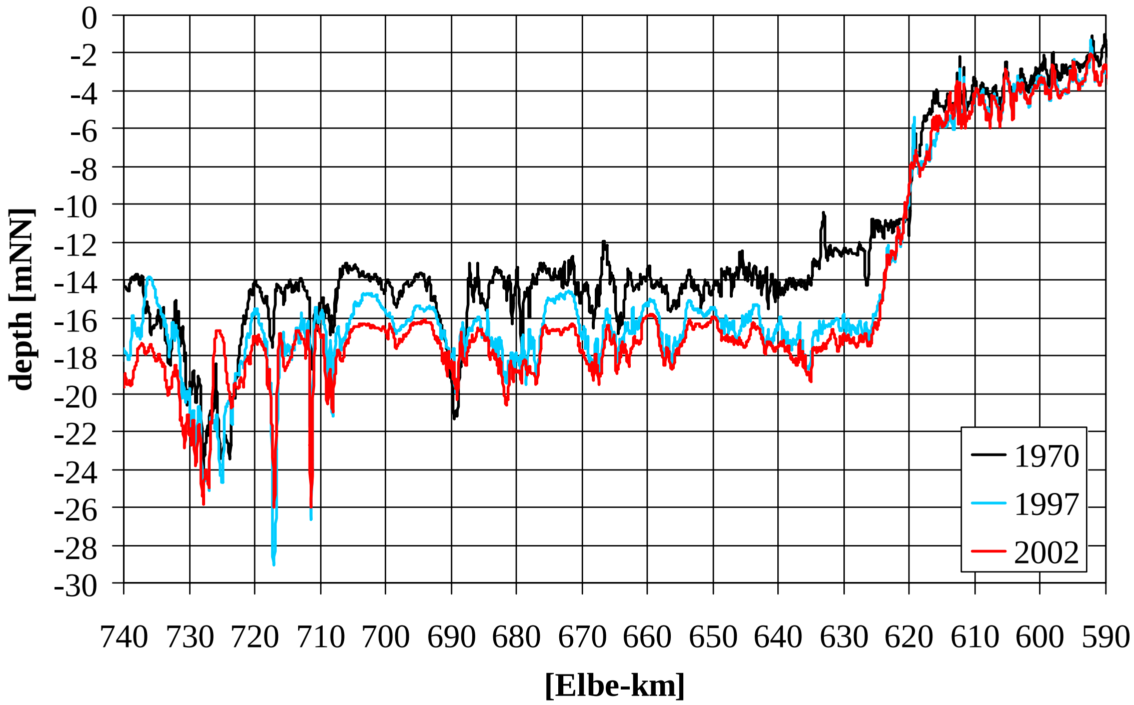

Figure 9 Measured depths in a long section along the middle of the fairway, 1970, 1997 and 2002.

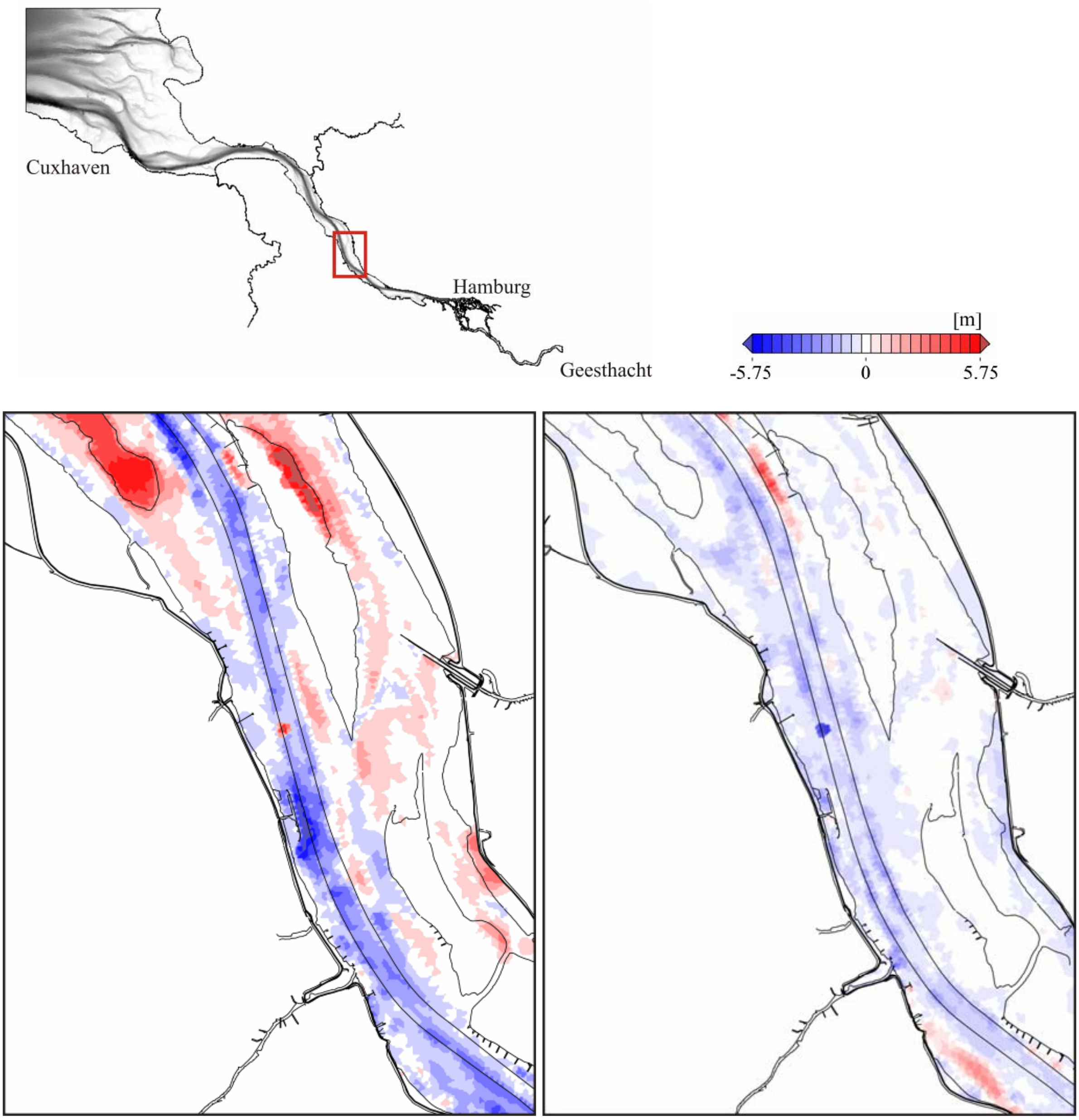

Figure 10 Difference of the measured depths between 1997 and 1970 (left picture) and between 2002 and 1997 (right picture).

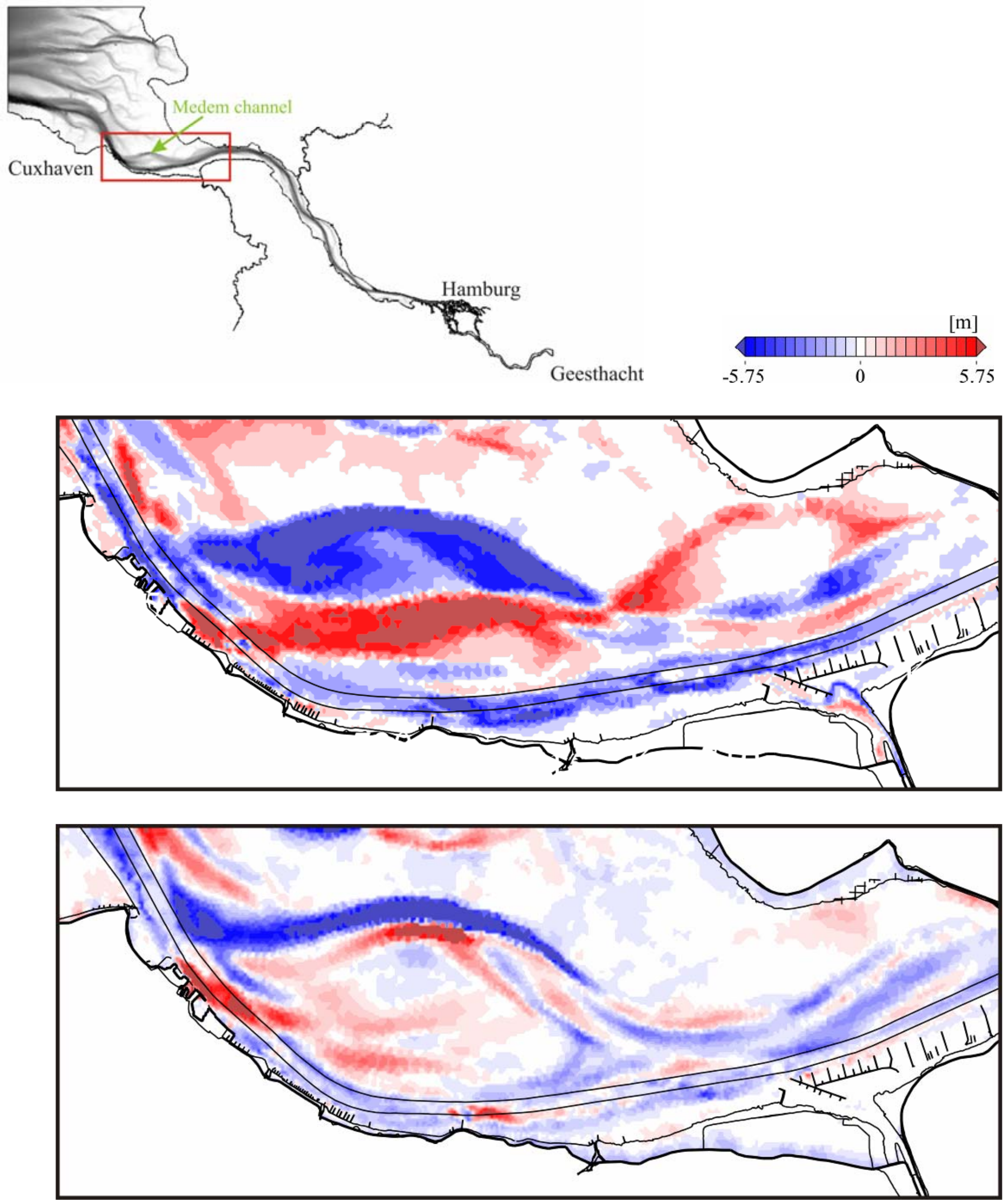

Figure 11 Difference of the measured depths between 1997 and 1970 (upper picture) and between 2002 and 1997 (lower picture).

3. RESULTS

3.1 Water Level

The tidal range in the outer estuary averages 3.2 m. In Hamburg it is calculated to 3.0 m for 1970 and nearly 4.0 m for 2002. The increasing tidal range in Hamburg results from an increase of the high tide of about 35 cm as well as from a decrease of the low tide (about 60 cm) between 1970 and 2002. That the increase of the tidal range at gage St. Pauli, Hamburg, between 1970 and 2002 is similar as observed from measurements (Figure 3). Results for water level elevations are not further investigated, because this study is focused on sediment transport processes which are mainly influenced by current velocities and induced bed shear stresses.

3.2 Current velocities

In the following diagrams the black curve represents the result for 1970, the result for 1997 is visualized by the blue color and the red curve represents 2002. These colors will be retained for all figures. The mean ebb current velocity as well as the mean flood current velocity increases with each deepening. Figure 12 and Figure 13 show the depth averaged velocities in the middle of the fairway for the analyzed neap-spring-cycle. For all model runs the mean ebb current velocity in the Outer Elbe (km 740 - km 700) is larger than the mean flood current velocity. Further landward the model results show mean flood current velocities which are greater than the mean ebb current velocities, especially upstream km 680.

The same tendency is visible in the maximum velocities. In Figure 14 and Figure 15 the three-dimensional results of the maximum velocities are shown in the middle of the fairway. The maximum ebb current velocities occur between km 735 and km 705. The red color indicates a velocity of 2.2 m/s to 2.6 m/s. These high velocities concentrate on the upper half of the water column. From km 660 to km 630 the result for 1970 shows maximum ebb current velocities between 0.6 m/s and 1.0 m/s. These velocities increase up to 1.4 m/s for the model run 2002.

The changes of the maximum flood current velocities are obvious for the section of the Elbe estuary between km 680 to km 630. While the results for 1970 show values between 0.8 m/s and 1.2 m/s, those for the bathymetry of 2002 are up to 1.8 m/s in the upper half of the water body. Near the bottom the velocities increase as well.

Concerning the sediment transport processes in the Elbe estuary the changes of the maximum flood current velocity between km 680 and km 630 are important. If the flood current velocity increases stronger than the ebb current velocity, the sediment transport becomes more and more flood dominant (tidal pumping effect) and increases the siltation in the harbor of Hamburg. The minor ebb current velocity is not able to remobilize all sediments which settle down during capsizing.

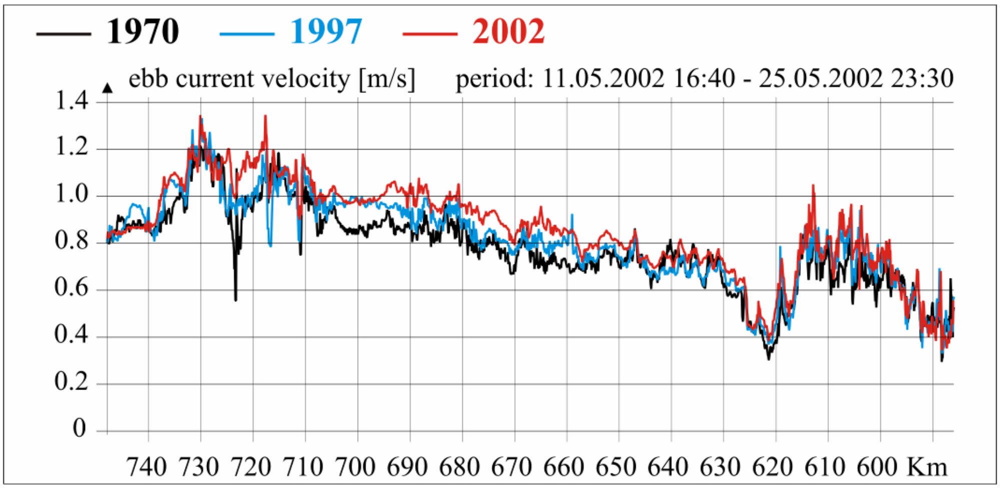

Figure 12 Mean ebb current velocity in the middle of the fairway 1970, 1997 and 2002.

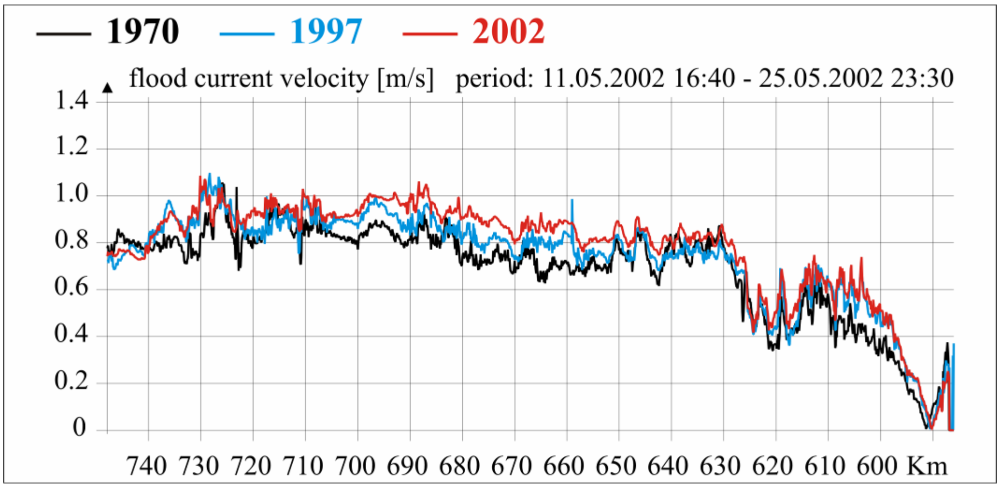

Figure 13 Mean flood current velocity in the middle of the fairway 1970, 1997 and 2002.

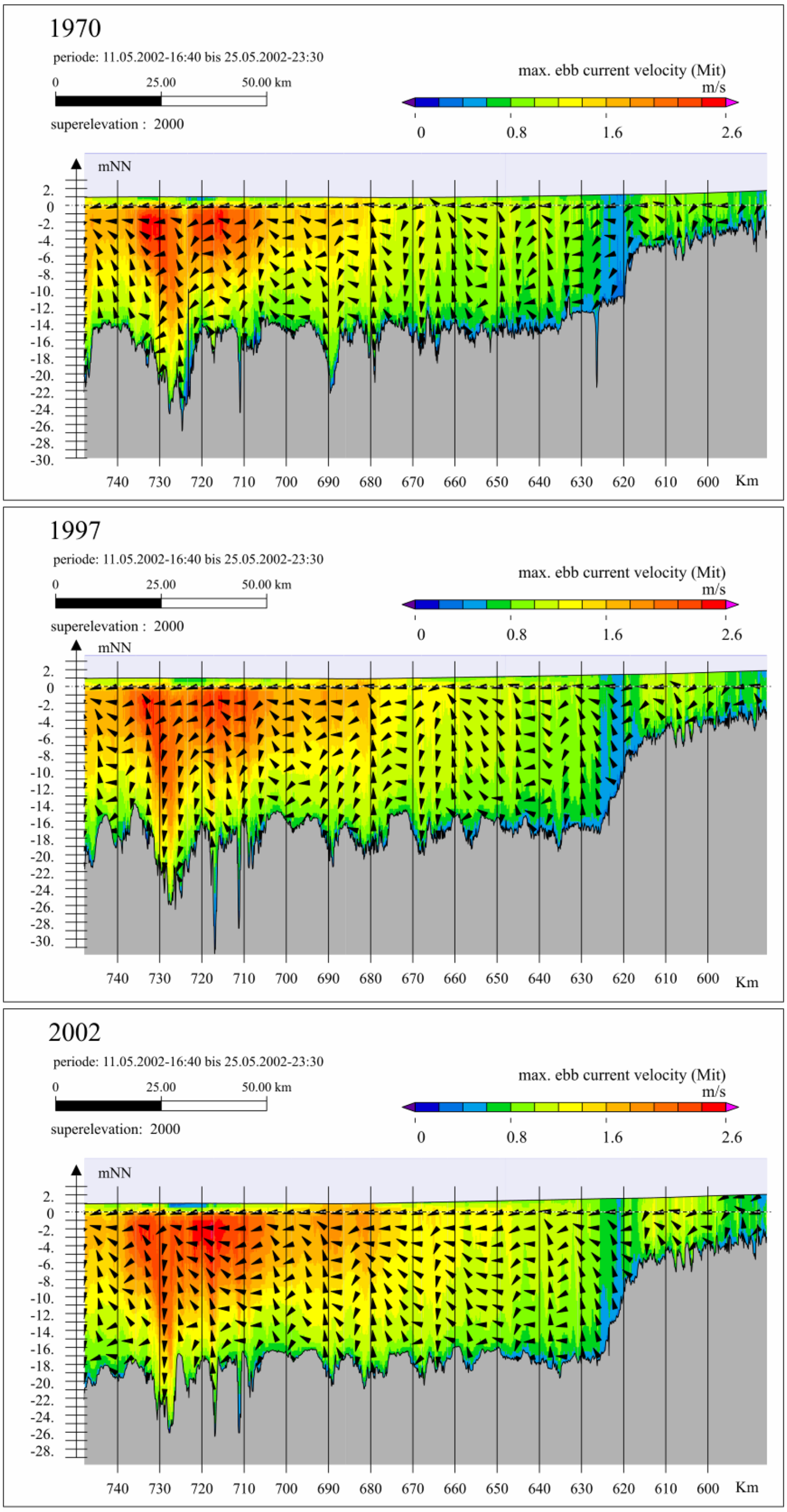

Figure 14 Maximum ebb current velocities in the middle of the fairway 1970, 1997 and 2002.

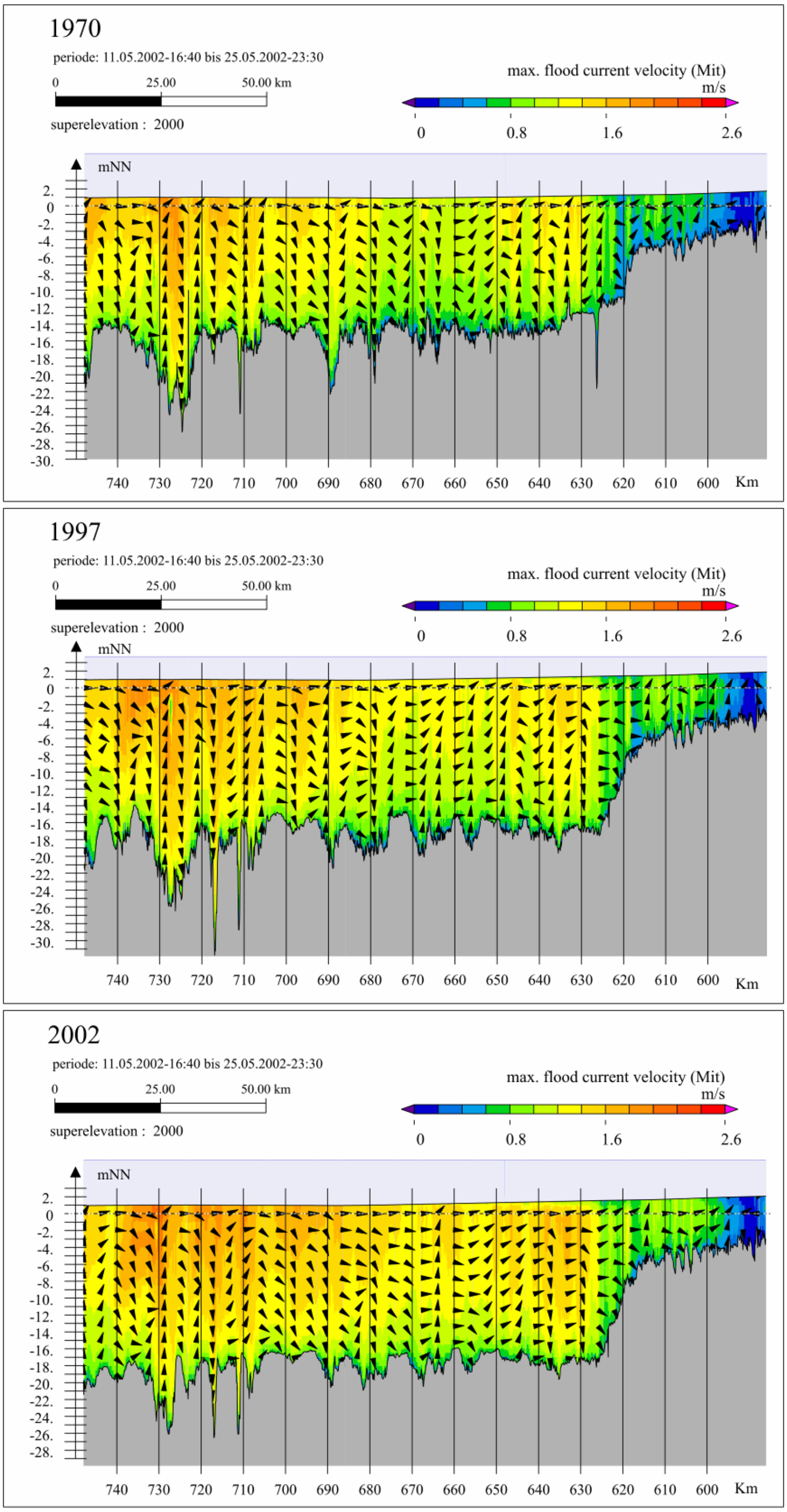

Figure 15 Maximum flood current velocities in the middle of the fairway 1970, 1997 and 2002.

3.3 Salinity

Changes of the mean salinity are noticeable. Figure 16 shows the mean depth averaged salinity in the Outer Elbe for the bathymetries of 1970, 1997 and 2002. By comparing the colored gradients around the dashed lines it is obvious that the brackish water zone moves upstream with each deepening of the fairway. This effect is important e.g. for ecological problems, but in this study it will not be further elaborated.

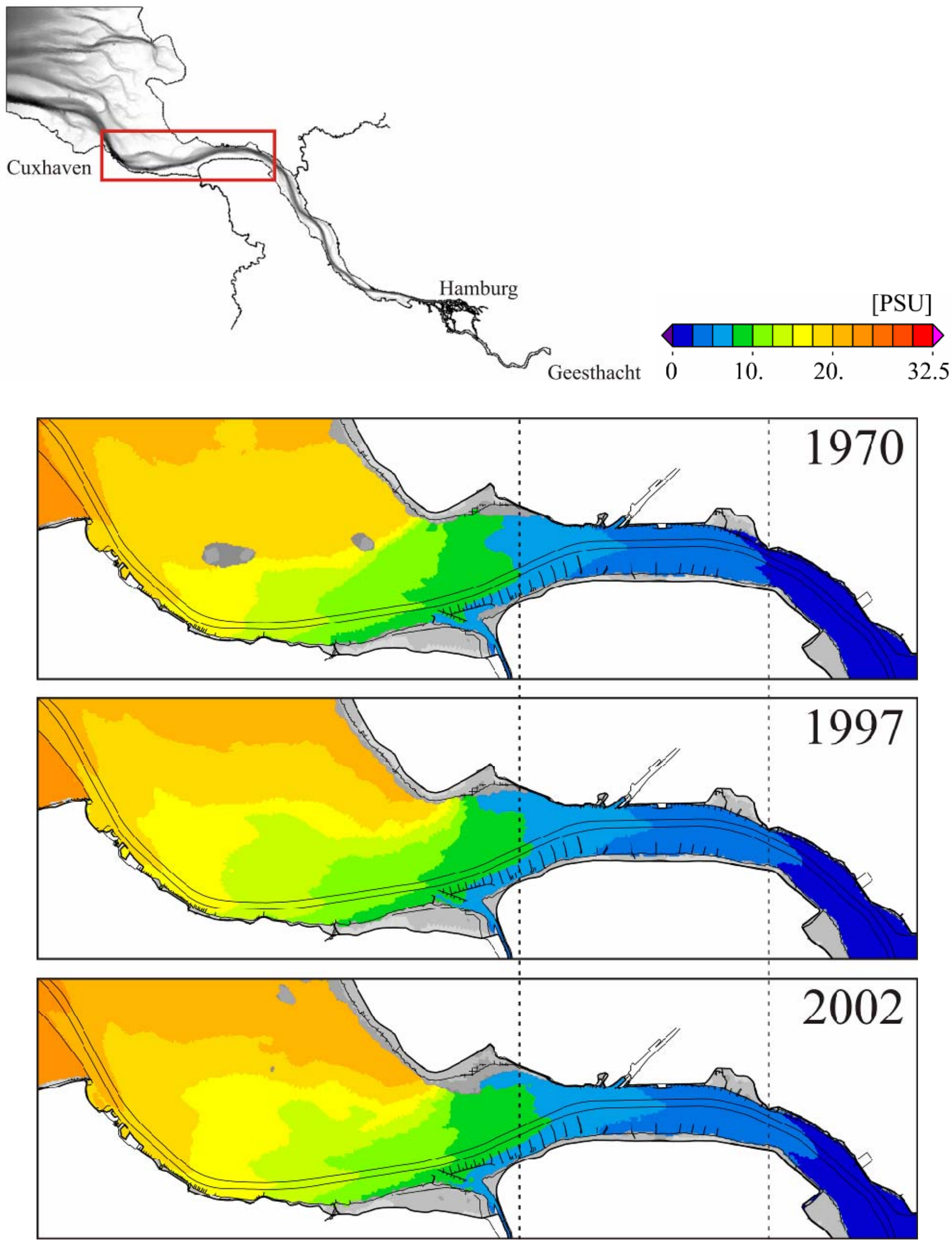

Figure 16 Mean salinity 1970, 1997 and 2002.

3.4 Suspended sediment

The mean concentration of suspended sediment in the middle of the fairway is shown in Figure 17 for each model run. The existence of a turbidity maximum with sediment concentrations up to 0.2 kg/m³ is clearly visible. As a result of the higher current velocities calculated in the model runs for 1997 and 2002 more sediment eroded from the bottom. The concentration of suspended sediment in the fairway increases and the expansion of the turbidity zone grows. This tendency can be seen better in Figure 18 and Figure 19 where the differences between the model results are shown. The red color indicates a higher sediment concentration for 1997 than 1970 (Figure 18) and respectively higher concentration for 2002 than 1997 (Figure 19).

Figure 20 shows the net transport of suspended sediment in the Elbe estuary analyzed for cross sections defined every 1 km along the Elbe estuary. Positive values indicate a resulting transport upstream. From km 680 up to the harbor of Hamburg sediment is transported upstream due to the stronger flood current. It will be settled down during the slack tide, and with the weaker ebb current less sediment is moved downstream. This tendency is already visible when the bathymetry of 1970 is compared with the bathymetry of 1997 and 2002.

The net transport of suspended sediment was enhanced with each deepening from 1970 to 2002. A distinct reason for the strong increase of siltation rates in the harbor of Hamburg after the last deepening is not observable in this figure, but regarding this question several other important influences must considered. The analyzed sediment transport patterns result only from suspended sediment transport. Bed-load transport is also calculated and it is also flood dominant, but not analyzed in the same way as suspended sediment transport in this study.

However the model results are valuable and gave an important insight in the sediment transport regime of the Elbe estuary. A steep gradient of the net transport of sediment between two cross sections means that sediment must remain in that area. For example between km 670 and km 660 about 3.000 tons of suspended sediment remain at each tide (Figure 21). This result is realistic because in this area maintenance dredging is necessary. Figure 22 shows a contour plot of the difference of the net transport between the results for 2002 and 1997. The difference of net transport is also dominated by the red color. So it is visible in which parts of the Elbe estuary the net transport increases. The distributaries are not affected heavily by this development.

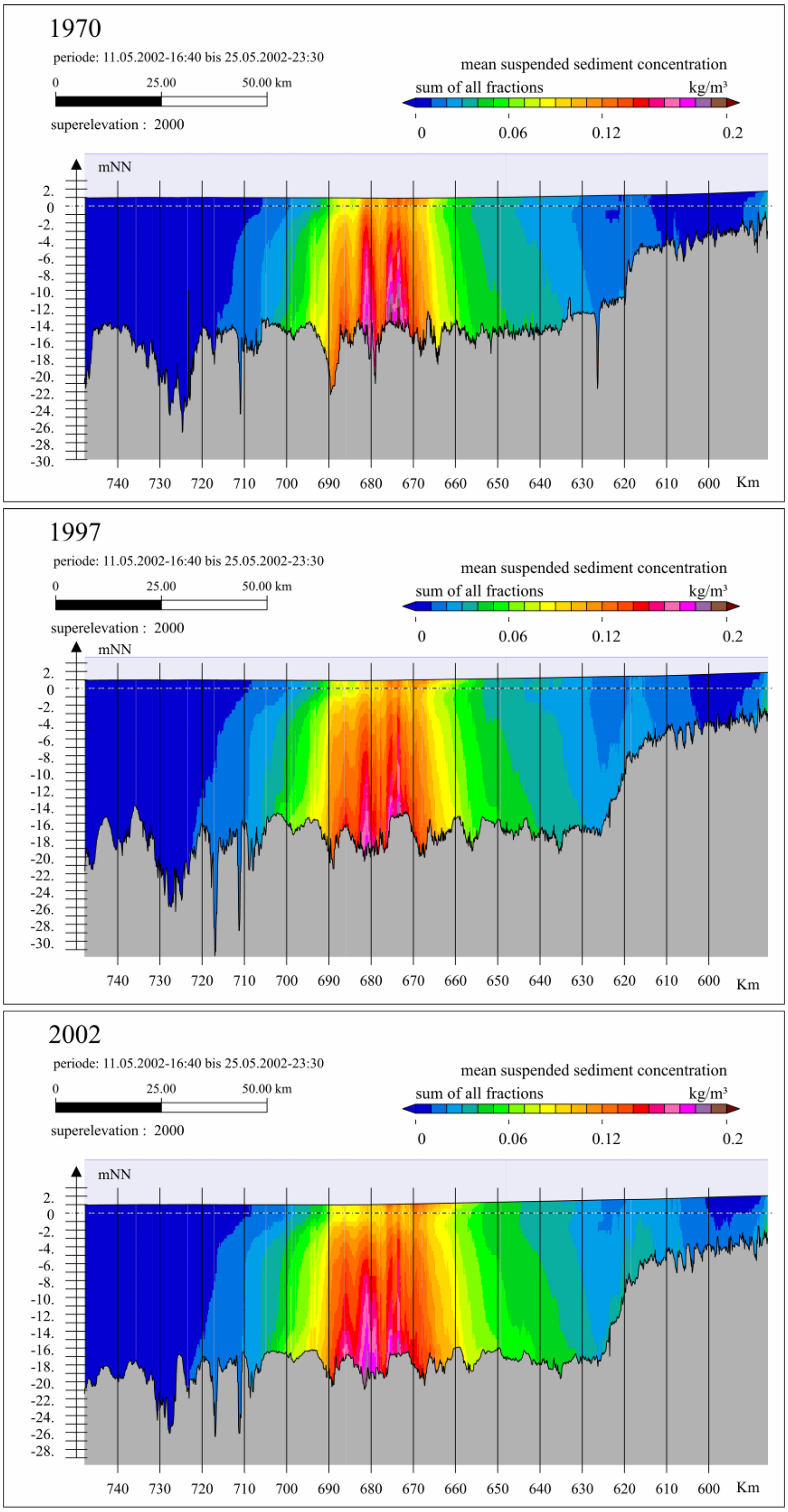

Figure 17 Mean suspended sediment concentration in the middle of the fairway 1970, 1997 and 2002.

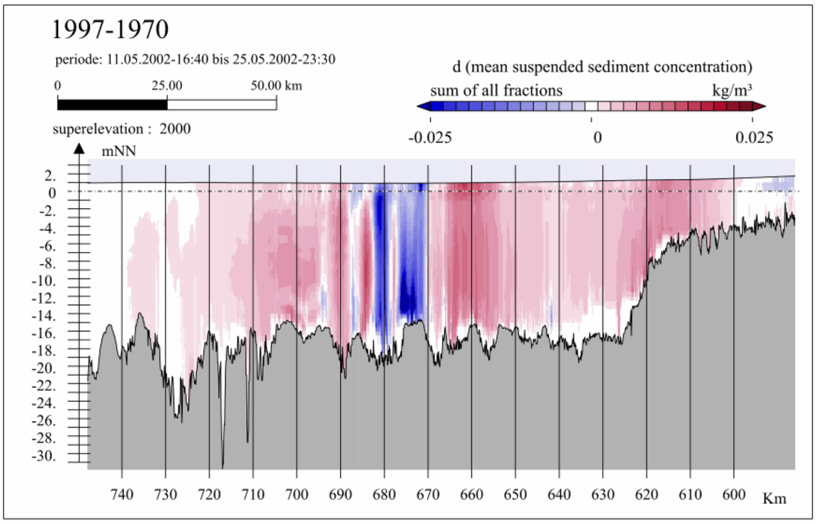

Figure 18 1997-1970: Difference of mean suspended sediment concentration in the middle of the fairway.

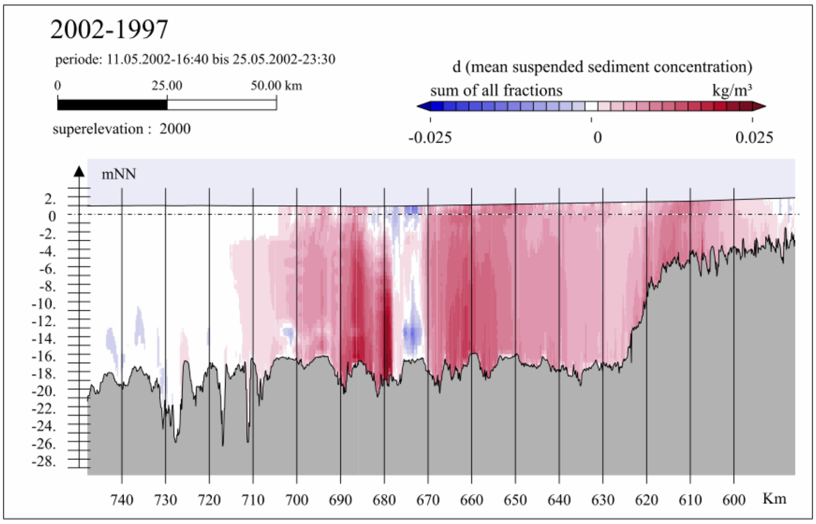

Figure 19 2002-1997: Difference of mean suspended sediment concentration in the middle of the fairway.

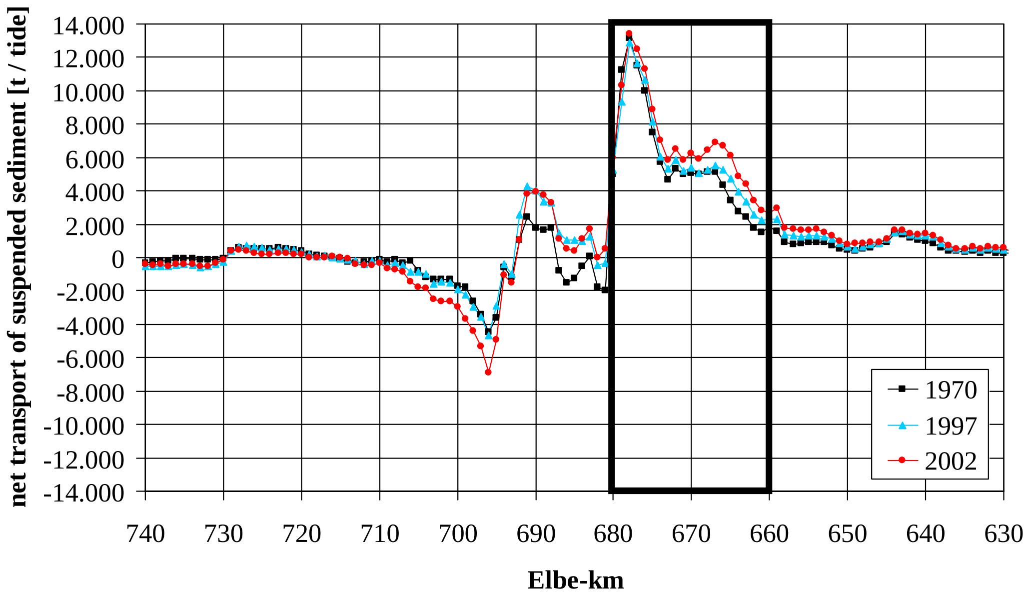

Figure 20 Net transport of suspended sediment in the middle of the fairway 1970, 1997 and 2002.

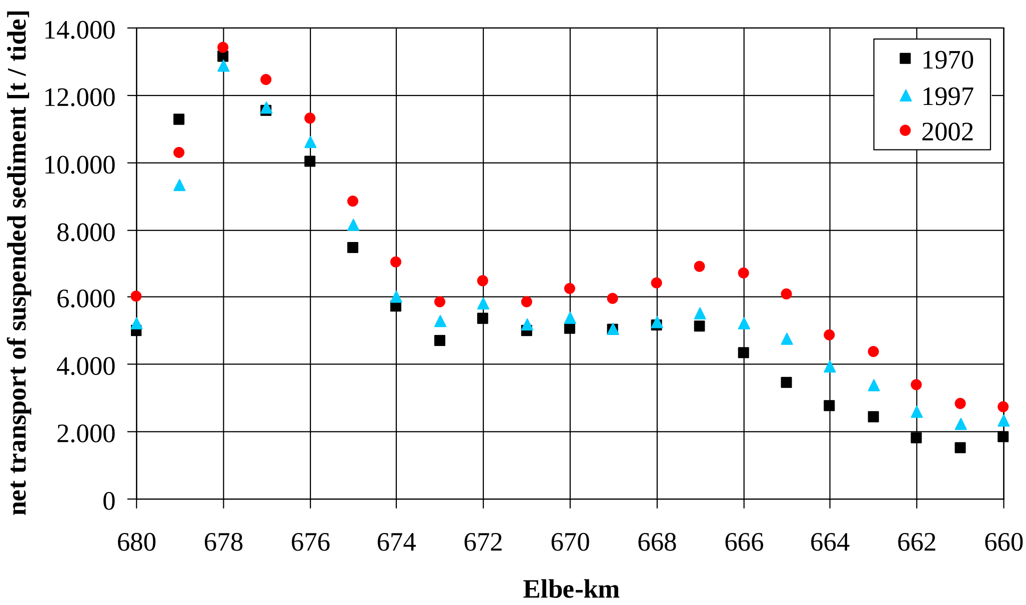

Figure 21 Net transport of suspended sediment in the middle of the fairway 1970, 1997 and 2002 - km 680 to km 660.

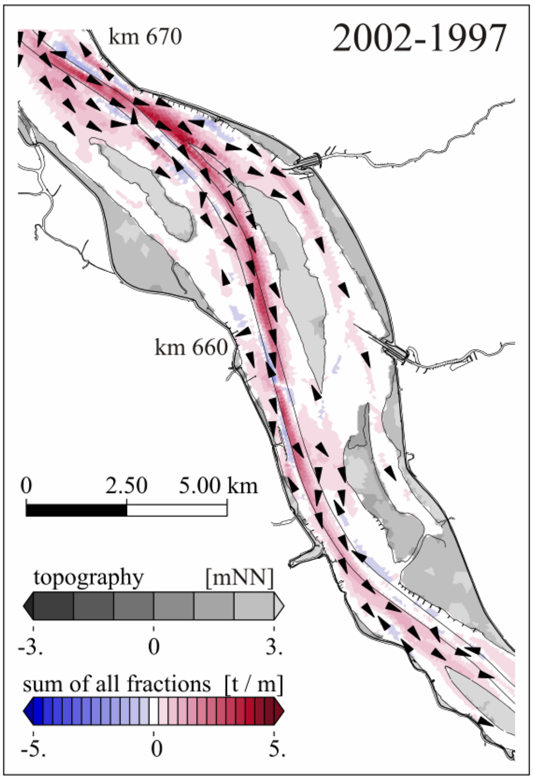

Figure 22 Net transport of suspended sediment: Difference 2002-1997

4. OUTLOOK

In this paper three model runs were compared to each other. Only the bathymetry representing the states for 1970, 1997 and 2002 was changed. It was shown that the tidal range increases from 1970 and 2002 in the Lower Elbe. The ebb current velocities as well as the flood current velocities in the middle of the fairway increase. The brackish water zone moves further upstream. A higher suspended sediment concentration upstream the turbidity zone was observed. Furthermore the net transport rates of suspended sediments were analyzed. It was shown, that for all bathymetries the region upstream the turbidity zone is dominated by the flood current. A net sediment transport upstream - so called ‘tidal pumping’ - takes place and was enhanced with each deepening.

This paper describes the first steps of an extensive investigation. The aim is to get knowledge of the sediment transport regime of the Elbe estuary, the resulting morphodynamical behavior and the reason for its changes in the last decades. This topic is very complicated, because there have been many anthropogenic measures as well as natural morphodynamics. It is not possible to relate reactions of the system only to one cause. In the majority of cases it is an interaction of several changes. To find out how different changes of the bathymetry affect each other, it is necessary to investigate it step by step and in detail. This hindcast study will be extended by other historical states for example 1985, 1992 and 2000. Furthermore only the deepening of the fairway without natural changes of the bathymetry will be analyzed to get an idea of the anthropogenic caused effects. At this time this study will be limited to the last 30 years, because older bathymetry data do not have the quality which is necessary to construct a computational grid.

Furthermore it will be necessary to expand the simulation and analyzing periods so that long-term accumulating processes can be understood. In these model runs dredging and dumping must be taken into account. This aspect is not considered in the analysis of this paper.

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